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EFFECT OF CRYSTALLOGRAPHIC TEXTURE ON THE MECHANICAL AND BALLISTIC PROPERTIES OF STEEL ARMOR

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FOREWORD

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Effect of Crystallographic Texture on the Mechanical and Ballistic Properties of Steel Armor

by Hsun Hu

Abstract

Continuing the study of the effect of crystallographic texture on the mechanical and ballistic properties of steel armor, 1/2-inch-thick plates of a medium-carbon 5Ni-Si-Cu-Mo-V steel were produced with a (110) or an $\sim$(111) texture of various intensities. Although the intensities of these textures in the present plates (2.80 or 2.45 times random) were as strong as those in the small-size specimens previously processed under strictly controlled conditions, their effects on the ballistic performance were not sufficiently great to be of practical significance. For both these textures and at the relatively low intensity levels, the V_{50} ballistic limits appeared to increase with increasing texture intensity. Consistent with the relatively low texture intensities and ballistic limits, the spalling tendencies of the plates were mostly weak to moderate. By using the average diameter of the exit holes as an indicator of the tendency for back spalling, a qualitative correlation between the exit diameter and the through-thickness tensile strength of notched plate specimens was found. The application of a light deformation to recrystallized austenite prior to quenching produced a "hybrid" texture in the martensite and no significant improvements in the ballistic properties. Directions for further investigations in the immediate future are suggested.

Introduction

Results from two consecutive investigations[1,2]* conducted earlier at this Laboratory indicated that the ballistic properties of high-hardness steel armor plates can be influenced significantly by the crystallographic texture of the plate. For a medium-carbon 5Ni-Si-Cu-Mo-V steel, isothermal rolling at 1500°F to various total reductions in thickness, then quenching, produced strong (112)+(111) texture with various degrees of intensity in the martensite. The V_{50} ballistic limits of these textured plates, tested with 0.50-caliber projectiles at zero-degree obliquity, were substantially higher than that of random-textured plates at approximately the same hardness.[1] Similar improvements were also observed when the plates were tested with 0.30-caliber projectiles.[3] In a following investigation,[2] it was shown that the reproducibility of the (112)+(111) texture and of the ballistic property improvements of these plates were excellent. Moreover, the results showed also that after appropriate corrections were made for the thickness of the test plates,[4] the corrected values of the V_{50} ballistic limit increased linearly with the texture intensity.[2] The texture dependence of the ballistic limit was similarly observed when the plates were tested at various degrees of obliquity.[5]

In addition to the (112)+(111) texture, which was produced by direct quenching of the deformed (by isothermal rolling at 1500°F)

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*See references.

austenite, two other kinds of textures, a (110) type and an ~(111) type were produced in small-sized exploratory specimens (0.10 to 0.20 inch in thickness).[1,2] As shown previously,[1] the (110)-type texture was produced by recrystallizing the isothermally rolled austenite into a cube-textured austenite, then quenching it to martensite. Unfortunately, the intensities of the (110) texture developed in the 0.5-inch-thick plates were not significantly higher than random because of experimental difficulties encountered at that time. Consequently, the effect of the (110) texture on the mechanical and ballistic properties of the 0.5-inch-thick armor plates could not be established from that earlier investigation.[1] However, it was believed that the experimental difficulties could be largely overcome by improving the processing techniques.

The ~(111)-type texture was produced by direct quenching of the isothermally cross-rolled austenite to martensite.[2] Production of this texture in the fully processed 0.5-inch-thick plates has not yet been attempted. Within the load capacity of the hot-rolling mill at the Laboratory, the ~(111) texture with reasonably high intensities could be produced in 0.5-inch-thick armor plates.

As a continuation of the previous investigations[1,2] on the same general subject, the present research program was undertaken in an attempt to fulfill the following purposes: (1) The development of a (110)-type texture with various intensities in the fully processed 0.5-inch-thick armor plates; (2) the development of a ~(111)-

type texture with various intensities in the fully processed 0.5-inch-thick armor plates; and (3) a study of the effects of these textures on the mechanical and ballistic properties of the plates. Since Ghosh and Paton[6)] have recently made some calculations about the relative resistance to shear and to through-thickness compression for several ideal orientations of texture of plates, the experimentally determined properties were compared with the calculated properties as a matter of scientific interest.

Material and Procedure

Steel Composition and Ingot Dimensions

Two 500-pound (227 kg) heats having the same nominal composition of those steels used in earlier investigations[1,2)] were vacuum-melted and cast into two ingots at the Laboratory. The dimensions of the ingots were also the same as those of the ingots made previously, namely, 7 by 12 by 24 inches (180 by 300 by 600 mm). One of the ingots (No. 732) was processed to produce the (110) texture with various degrees of intensity in the final plates by quenching the recrystallized austenite. The other ingot was processed to produce the ~(111) texture with various degrees of intensity in the final plates by quenching the cross-rolled austenite. Check analyses of samples taken from the fully processed plates, which were rolled to various reductions to the same final thickness (0.55 inch or 14 mm) are shown in Table I. The results indicate that the armor plates processed in the present investigation were homogeneous in

composition, and within narrow variation limits these compositions matched closely with those of earlier steels.[1,2]

Hot-Rolling Procedures

Preliminary Hot Rolling and Preparation of the Intermediate Pieces. For the ingot (No. 732) to be processed to the final plates with the (110) texture of various intensities, the procedures of preliminary hot rolling to the various intermediate thicknesses, namely 5.50, 2.75, 1.85, and 1.40 inches (140, 70, 47, and 36 mm), respectively, were largely the same as those reported previously.[2] The ingot was hot-charged into a preheating furnace at 2250°F (1230°C), soaked for two hours, and then rolled from the 7 inches of the ingot thickness to a slab of 5.50 inches. A predetermined length was torch-cut from the bottom end of the slab, and the remaining slab was then reheated to temperature in the furnace for about 20 minutes. The slab was then further rolled to the next intermediate thickness (2.75 inches), and another predetermined length was torch-cut from the previous cut end of the rolled piece. The reheating, hot-rolling, and torch-cutting procedures were repeated until the piece was finally rolled to 1.40 inches in thickness.

All these pieces of intermediate thicknesses were first cooled in air, or for the thicker pieces, with a light water spray to accelerate the cooling rate in the high-temperature range to avoid the formation of massive phases. From approximately 900°F down to the ambient temperature, these pieces were cooled slowly in

vermiculite to minimize the internal stresses due to phase transformation in the low-temperature region, which was found responsible for the hairline cracks observed on the cut faces of the intermediate pieces, and for the edge-cracking that frequently occurred in the final rolling to 0.55-inch armor plates.[2)]

Slabs of these four intermediate thicknesses were subsequently cut longitudinally along the centerline of the width into two halves. Thus, each piece became only 6 inches (152 mm) wide in final rolling. As in earlier practices,[1,2)] a hole (5/32 inch or 4 mm in diameter) was drilled on the cut face and to the geometric center of each piece, and a thermocouple was inserted for temperature monitoring during the final isothermal rolling operations.

For the ingot (No. 733) to be processed to the final plates with the ~(111) texture of various intensities by quenching cross-rolled austenite, only three intermediate thicknesses, namely 2.75, 1.85, and 1.40 inches, were produced in the preliminary hot-rolling operations. This was dictated by the limited load capacity of the laboratory rolling mill. For isothermal rolling the armor steel at 1500°F (816°C), the separating force for rolling 6-inch-wide plates at the reduction rates employed was about 70 percent of the load capacity of the mill. Calculations indicated that, with the maximum dimensions of 7.5 by 7.5 by 0.55 inches (190 by 190 by 13 mm) for the final plates, it was possible to process the intermediate pieces by isothermal cross rolling at 1500°F to 60, 70, and 80

percent reductions in thickness to 0.55-inch-thick plates. For a 90 percent reduction in thickness in the final processing by isothermal cross rolling at 1500°F to 0.55-inch-thick plates, either the size of the intermediate piece would be too small to handle in rolling, or the width of the piece would become too large to roll within the load capacity of the mill. Accordingly, 90 percent reduction by cross rolling was not possible in the present investigation.

The preliminary hot processing for this ingot (No. 733), such as rolling, torch-cutting, reheating the remaining portion of the slab for further rolling to next smaller thickness, and cooling these intermediate pieces, was all the same as the procedures employed for the other ingot (No. 732).

A number of square pieces were cut from each of the three intermediate slabs 2.75, 1.85, and 1.40 inches thick. The dimensions of the square pieces to be cross-rolled in final processing, and the estimated dimensions of the final plates after cross rolling to 60, 70, and 80 percent reductions are shown in Table II.

For these intermediate pieces to be cross-rolled in the final processing, no monitoring thermocouple was used because the hole with the embedded thermocouple remains, being centrally located inside the plate, would certainly impair the ballistic testing results. In addition, the dimensions of the cross-rolled plates, as estimated in Table II, were considerably smaller than the 6- by 12-inch plates normally used for ballistic testing. During the isothermal cross-rolling operations, it was necessary to rely either

on the optical pyrometers installed on the rolling mill, or on the elapsed time, the correlation of which with temperature can be predetermined from calibration runs in cross rolling identical pieces. For these calibrations, a few of the square pieces were each provided with a centrally located hole to accommodate a thermocouple for calibration.

Final Hot Rolling and Subsequent Treatments. In consideration of the difference between the martensite transformed from the deformed austenite with a highly dislocated substructure* and the martensite transformed from the recrystallized austenite with highly perfect grains, an attempt to reduce this difference was practiced in the present investigation. This was done by isothermally rolling at 1500°F half of the intermediate pieces from Ingot 732 through the next-to-final pass, recharging the rolled piece into the furnace at 1700°F for 30 minutes for recrystallization to cube-textured austenite, then rolling the final pass at 1500°F to 0.55 inch thick, followed by water-spray quenching to room temperature (identified as Part 1 of Ingot 732). The remaining intermediate pieces from Ingot 732 were isothermally rolled to various reductions to 0.55 inch thick, recharged into the furnace at 1700°F for 30 minutes for recrystallization to cube-textured austenite, then cooled in air to 1500°F followed by water-spray quenching to room temperature (identified as Part 2 of Ingot 732).

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*Such as the (112)+(111) textured martensite which was produced by direct quenching the isothermally rolled austenite, or the ∿(111) textured martensite which was produced by direct quenching the isothermally cross-rolled austenite.

In final hot rolling, all the intermediate pieces were reheated for two hours at 1700°F and isothermally rolled at 1500°F. As was the case in the previous investigation,[2)] for the more massive pieces (2.75 and 5.50 inches thick), it was necessary to start rolling at a somewhat higher temperature (for example, 1575 and 1600°F) to avoid excessive cooling at the corners and edges of the piece. Although start-rolling temperature was somewhat higher than the intended temperature for isothermal rolling (1500°F), the temperature of the working piece was allowed to drop to 1500°F in the first few passes.

In processing the Part 1 material of Ingot 732, because the plates were too long for the furnace after rolling through the next-to-final pass, it was necessary to torch-cut the rolled piece before recharging the plates into the furnace for annealing for recrystallization. These torch-cutting and recharging operations had to be conducted rapidly to avoid cooling the rolled plates below the M_s temperature (~520°F). Any substantial formation of the martensite would eliminate the possibility of producing cube-textured austenite in the recrystallization anneal. Examination of the texture of the recrystallization-annealed and quenched plates will reveal whether or not martensite transformation occurred prior to recrystallization.

In the final processing of the Part 2 material of Ingot 732, the torch-cutting operation prior to recrystallization anneal on the finish-rolled plates was completely eliminated to avoid the

possibility of any phase transformation to martensite prior to recrystallization, as discussed above. The slabs of intermediate thicknesses were each cut into two pieces to shorten the length of the intermediate pieces for final rolling. A thermocouple hole was provided in each of these intermediate pieces. The final hot rolling, the reannealing of the finish-rolled plates for recrystallization, and the water-spray quenching of the recrystallization-annealed plates after air cooling to 1500°F were all conducted in the usual manner.

The Ingot 733 material was divided into two groups for the final processing of the intermediate pieces by isothermal cross rolling at 1500°F to 60, 70, and 80 percent reduction. The only difference between the two groups was the method of monitoring the temperature of rolling. In the first group, the rolling temperature was controlled by time elapsed during the rolling operation. The time and temperature correlation was obtained from a few trial pieces, each with an inserted thermocouple, and the time and temperature variations during the rolling operation were recorded. This time schedule was closely followed in rolling the intermediate pieces of identical sizes to the trial pieces. In the second group, the rolling temperature was controlled by an infrared optical pyrometer installed at both the entrance and exit sides of the rolling mill. Identical cross-rolling reduction schedules were employed for the pieces processed in both groups. As mentioned earlier, because of load limitations of the rolling mill, the finished plates were

produced by cross rolling the intermediate pieces individually. It would be assumed that all individual plates, cross-rolled to the same reductions with the same rolling schedules, would be essentially identical in structure, texture, and properties.

All fully processed and quenched plates were given a tempering treatment of one hour at 350°F (177°C) before specimens were prepared for various examinations or tests.

Results and Discussion

Texture of Plates Produced by Quenching the Recrystallized Austenite

Recrystallized Austenite Lightly Deformed Before Quenching (Plates from Part 1 of Ingot 732). The intensional introduction of a substantial quantity of dislocations into the recrystallized austenite by applying the last pass of rolling to the reannealed (1700°F for 30 min) plates prior to quenching resulted in noticeable changes in the texture of the martensite. As shown in Figures 1 and 2, which are the (110) and (200) pole figures, respectively, determined from the midthickness section of the plates rolled 60 to 90 percent from the Part 1 material of Ingot 732, the texture was essentially a mixture of the (112)+(111) and the (110) with variable proportions of the two types of textures.* A rough estimate of the relative prominence of these two types of textures

*The techniques for X-ray pole figure determinations and the designations of the ideal orientations of the textures were all the same as those used and described in previous investigations.[1,2]

can be indicated by the relative intensities of the specific locations in the (110) pole figures. For example, position D and position R, as marked in Figure 1D, are the locations where the intensity maxima for the (112)+(111) type and the (110) type textures, respectively, are normally observed. For the 80 and 90 percent rolled plates, the (110) texture appears to be stronger than the (112)+(111) texture, whereas for the 60 and 70 percent rolled plates, the reverse is indicated.

This observation can be readily explained on the basis of the relative amount of rolling reduction by the final pass. In the more lightly rolled plates (total rolling reduction was 60 or 70%), the amount of reduction in the final pass corresponded to a higher percentage of the total rolling reduction than in the heavily rolled plates (total rolling reduction 80 or 90%). As a consequence, the texture in the finishing plates was a mixture of the (112)+(111) and the (110) types, with variable proportions.

Aside from the fact that the intensities of these texture components were very \ , such "hybrid" textures would make the study of mechanical and ballistic properties of the armor plates as a function of crystallographic texture more difficult. The application of the last rolling pass to the recrystallized austenite before quenching produced complex textures of the martensite unsuitable for the intended studies. However, to provide additional information which might be useful in the future, the structure and

properties of these plates were included along with those of other plates in the present investigation.

<u>Recrystallized Austenite Undeformed Before Quenching (Plates from Part 2 of Ingot 732)</u>. Plates processed from the intermediate pieces of the remaining half of the ingot by quenching the recrystallized austenite without applying a light deformation prior to quenching showed satisfactory development of the (110) texture. The (110) and (200) pole figures of these plates are shown in Figures 3 and 4, respectively. The intensities of the texture of the present plates were substantially higher than those of the corresponding plates produced previously.[1)] For example, the average intensity maxima of the (110) pole figure for the plate rolled 90 percent in the present investigation were 2.80 times random (Figure 3D), whereas those of the corresponding plate processed previously were only 1.40 (Table IX and Figure 6 of Reference 1). As a matter of fact, the texture intensities of the present plates were equal to or higher than those of the small-size specimens processed in the exploratory investigations (Figure 5 of Reference 1). However, these intensities of the (110) texture, ranging from 1.65 to 2.80 times random for the plates rolled 60 to 90 percent, recrystallized, then quenched (Figure 3, A to D), were substantially lower than those of the (112)+(111) texture, ranging from 3.75 to 9.05 times random for plates rolled 60 to 90 percent and directly quenched (Figure 1, A to D of Reference 2).

Of course, the intensity maxima of the (110) pole figure for the (112)+(111) type of textures represent the major axes of rotation for the orientation spreads, or a common pole for the various orientations that are present. Hence, the intensity of that particular (110) pole is outstandingly high. The wide areas of the intensity maxima shown by the pole figure for the (110) texture (for example, Figure 3D) suggest that either the cube texture of the recrystallized austenite was not very sharp and strong, or the selection of the Kurdjumov-Sachs variances for the austenite-to-martensite transformation was more diversified when transformation occurs in the recrystallized than in the heavily rolled austenite matrix. To compare the relative merit of the (110) texture and the (112)+(111) texture in affecting the mechanical and ballistic properties of the plates on an equal basis, the intensity of the (110) texture will have to be further increased.

Texture of Plates Produced by Quenching the Cross-Rolled Austenite

As mentioned in the processing procedures, the intermediate pieces of the Ingot 733 material were final-processed by isothermal cross rolling in two groups. In the first group, the isothermal rolling temperature was controlled by time elapsed during the rolling operation. In the second group, the rolling temperature was monitored by an infrared optical pyrometer. The texture and properties of these plates were essentially the same regardless of

the two methods for temperature monitoring during the rolling operations. Therefore, there is no need to distinguish these two groups of plates.

The textures of the plates isothermally cross-rolled at 1500°F to the various reductions in thickness, then quenched, are shown in Figures 5 and 6 by the (110) and (200) pole figures, respectively. The RD_1 and RD_2 designate the first and the second rolling directions, which are orthogonal to each other. The intensities of the textures increased with increasing reduction, from 2.02, to 2.29, to 2.45 times random for rolling reductions of from 60, to 70, to 80 percent (Figures 5, A to C). These textures were, in fact, quite comparable to those observed previously in small-size exploratory specimens.[2)]

In comparison with the texture intensity in straightaway-rolled and quenched plates,[2)] the cross-rolled and quenched plates showed considerably lower texture intensities. Part of this difference may be accounted for by the fact that the intensity maxima in the (110) pole figure for the (112)+(111) type of texture happen to be the major axes of rotation for a continuous range of orientation spreads, hence the outstandingly high intensity of these particular (110) poles. However, examination of the textures of straightaway- and cross-rolled fcc metals and alloys, such as copper[7,8)] and α-brass,[8)] showed that the intensity maxima of their (111) pole figures had approximately the same intensity levels in both straightaway- and cross-rolled specimens. Thus, the observed low intensity of the texture of martensite produced by quenching

cross-rolled austenite may have been a consequence of more accelerated recovery during cross rolling at high temperatures, or of more diversified selection of the Kurdjumov-Sachs variances in the transformation of cross-rolled austenite. An in-depth study of these problems will be of great scientific interest and practical importance. No attempt was made in the present investigation to look into these problems, because they are beyond the scope of the intended studies.

Microstructure of the Plates

The microstructures of the quenched and tempered plates were examined by light microscopy, SEM (scanning electron microscopy), and TEM (transmission electron microscopy) on the longitudinal and transverse cross sections of the plate. For cross-rolled plates, specimens sectioned perpendicular to RD_1 and RD_2 (the first and second rolling directions, respectively) were examined in a similar manner although the two orthogonal rolling directions were essentially equivalent. The structural banding in the present plates was less prominent, even in the longitudinal section of the specimen, than in those plates processed previously[1,2] by quenching the straightaway-rolled austenite. In agreement with earlier observations on the small-size, cross-rolled and quenched specimens,[2] the structural banding in the present cross-rolled and quenched plates was only very faintly indicated in either of the cross sections.

The microstructures of the specimens rolled 60 and 90 percent, recrystallized, then quenched and tempered are shown in the SEM photomicrographs in Figure 7 (recrystallized austenite lightly deformed

and quenched) and in Figure 8 (recrystallized austenite undeformed before quenching). There are hardly any noticeable differences between the structures of these two series of specimens. For those plates that were cross-rolled 60 and 80 percent then quenched and tempered, the microstructures are shown in Figure 9. The martensite platelets appear to be shorter in length in the rolled and directly quenched specimens than in the specimens recrystallized (or recrystallized and lightly deformed) then quenched.

The microstructures of the same specimens, as revealed by TEM at 1000 kV are shown in Figures 10, 11, and 12. As can be noted, the prior austenite grain boundaries are more sharply delineated in the specimens recrystallized then quenched (Figure 10 or 11) than in the specimens heavily rolled then quenched (Figure 12). Even in the specimens that were quenched from recrystallized and undeformed austenite (Figure 11), high densities of dislocations were present in the martensite platelets.

Mechanical Properties of the Plates

In-Plane Tensile Properties. The in-plane tensile properties of the plates were determined by testing specimens 0.25 inch (6.3 mm) in diameter and 1-inch (25 mm) gage length, prepared along three directions in the plane of the plate. In addition to the commonly used longitudinal and transverse specimens (tensile directions being in the rolling and transverse directions, or in RD_1 and RD_2 of the cross-rolled plates), tensile properties in the diagonal direction,

that is, 45 degrees from the rolling and transverse directions (or from RD_1 and RD_2 in the cross-rolled plates) were also tested. Duplicate specimens in each direction were tested for each single plate; for the cross-rolled plates, specimens were prepared and tested from two or more plates for each rolling reduction. The purpose of this wide sampling, in particular for the cross-rolled plates, was to ensure that the plates were essentially identical, even though each plate was cross-rolled individually. Test results indicated that, within narrow scatter limits, the properties of the plates in the same category were practically the same.

The average in-plane tensile properties of the plates are shown in Table III for plates processed by quenching the recrystallized austenite with and without a light rolling deformation before quenching, and in Table IV for plates cross-rolled and quenched. As the first part of Table III shows, there is very little difference in the yield and tensile strengths, or in the reduction in area and total elongation of the plates as a function of rolling reduction. The relative amount of the rolling deformation of the final pass, which comprised a greater portion of the total rolling reduction in the lightly rolled than in heavily rolled plates, may have been compensated for the difference in yield strength between the lightly and heavily rolled plates (see Y.S. in the second part of Table III as a function of rolling reduction).

Comparison of the yield strengths along the longitudinal, diagonal, and transverse (L, D, and T, respectively) directions of

the plates shows a slightly lower strength in the diagonal direction than in either the longitudinal or the transverse direction (both of which were about equal) for the lightly rolled plates. This may have also been a consequence of the slight planar anisotropy introduced by the final-pass rolling reduction, as no such differences are indicated by the yield strengths of the plates shown in the second part of Table III. The ductility, as shown by both the reduction in area and the total elongation, of all these plates is lower in the transverse than in the longitudinal or the diagonal directions.

The slight increase in yield strength with increasing rolling reduction, as shown by the specimens quenched from recrystallized austenite without a light deformation before martensite transformation (part 2 of Table III), would ave to be a consequence of the increasing intensity of the (110) type textures (Figures 3 and 4), because there is hardly any noticeable difference in the fineness of the microstructures (Figures 8 and 11). However, such small differences (<4.0%) in strength are probably of no practical significance. As a matter of fact, these tensile properties of the present plates are in excellent agreement with those observed previously in similarly processed plates which did not show measurable improvements in the ballistic limits over the random-textured plates (Tables IV and IX of Reference 1).

Tensile properties of the cross-rolled and quenched plates are shown in Table IV. Theoretically, if the true strains produced

by cross rolling in the two rolling directions are the same, equal properties should be exhibited in the two orthogonal rolling directions, and the textures shown by the pole figures should exhibit four-fold symmetry. The fact that the textures of the present cross-rolled plates were not exactly symmetrical with respect to RD_1 and RD_2 (Figures 5 and 6) indicates the ideal cross-rolling conditions having not really been met in practice. Consequently, the mechanical properties, as shown by the ductility (reduction in area and elongation) in particular, are not identical in the longitudinal (RD_1) and transverse (RD_2) directions. The yield strengths of these cross-rolled and quenched plates, being similar to those of the recrystallized then quenched plates (Part 2 of Table III), increased with increasing rolling reduction.

Through-Thickness Tensile Properties of Notched Specimens. According to a suggestion made earlier by Richmond,[9] the resistance to spalling at a constant strain rate could be determined for plates by testing the through-thickness tensile strength under constrained conditions such as the sharply notched specimen, shown in Figure 13, in which $\varepsilon_1 = \varepsilon_2 \approx 0$. Previous results on selectively tested specimens appeared to be qualitatively consistent with the suggestion in that, for the strongly textured plates having the (112)+(111) texture, the tensile strength of notched specimens decreased with increasing texture intensity and with the tendency of back spalling in ballistic tests.[1] The results indicated also that the tensile strength of notched specimens was the highest for the random-textured plates, which showed practically no spalling upon ballistic impact.[1]

To provide additional tests of Richmond's suggestion, the through-thickness tensile strengths of notched specimens of the variously processed plates were determined. The results are summarized in Table V. For those plates that were quenched from the recrystallized austenite lightly deformed before quenching the tensile-strength data for notched specimens could not be discussed meaningfully as a function of total rolling reduction because of the complexities introduced by the effective straining from the last rolling pass, which varied with the total rolling reduction (see discussions in an earlier section). The tensile strengths of notched specimens of the cross-rolled plates tend to decrease with increasing rolling reduction, hence, with increasing texture intensity, and are, therefore, consistent with those of the (112)+(111) textured plates.

On the other hand, for those plates quenched from recrystallized austenite that was undeformed before quenching, the tensile strengths of notched specimens tend to increase (with the exception of specimen 732B-2, whose total elongation also seemed to be off substantially) with increasing rolling reduction and texture intensity. If this trend is confirmed, the tendency for back spalling of the (110) textured plates would be expected to decrease with increasing texture intensity. This would be a highly desirable feature for armor plates, because, according to Ghosh and Paton,[6)] the cube-on-edge, or {110}<001>, texture is as strong in through-thickness compression as the cube-on-corner, or {111}<112>, texture.

Charpy Impact Properties. The Charpy V-notch impact properties of the variously processed plates were tested in the longitudinal and the

transverse directions (RD_1 and RD_2 in cross rolling). The room-temperature impact energies are listed in Table VI. There were only small variations among the plates of each category and, as is usually the case, the impact energies were somewhat higher in the longitudinal than in the transverse directions. For the cross-rolled plates, the difference between the impact energies in the two rolling directions was substantially less—the average value in the longitudinal direction was slightly lower, whereas that in the transverse direction, slightly higher than in the straightaway-rolled plates.

Ballistic Performance of the Plates

The V_{50} Ballistic Limits. For ballistic testing, the quenched and tempered plates were surface-ground to remove oxide scale and decarburized layer, and the Rockwell C hardness of each plate was measured. These plates were then tested with 0.50-caliber projectiles at zero-degree obliquity to determine the V_{50} ballistic limits. The ballistic test results, together with the texture type and intensity and the thickness and hardness of the test plates, are summarized in Table VII for plates quenched from recrystallized austenite and in Table VIII for plates quenched from cross-rolled austenite.

As established previously,[2)] the V_{50} ballistic limit of random-textured plate of the present armor steel is around 2000 fps, with a scatter band of about 100 fps on either side of this mean value. The ballistic limits shown in Table VII are, therefore, not significantly different from the ballistic limit of a random-textured plate. Consistent with those observed V_{50} ballistic limits are the relatively

low texture intensities. Thus, the texture intensities of the present plates, even though they have been improved substantially since a weakly (110)-textured plate was first produced in an earlier investigation,[1] are much too weak to significantly influence the ballistic properties of the armor plates.

On the other hand, the ballistic limits of the cross-rolled and quenched plates showed somewhat higher values than those of random-textured plates even at such relatively low levels of texture intensities, Table VIII. Moreover, the observed ballistic limits, which represented the averaged values of several plates individually processed and tested, showed a fairly consistent tendency to increase with increasing texture intensity. It would be necessary, however, to further increase the intensities of the (110) and the $\sim$(111) textures substantially to ascertain their effects on the ballistic properties of these textured armor plates. For this purpose, additional studies would be required.

<u>The Tendency for Back Spalling</u>. Previous results[1,2] indicated that the tendency for back spalling increases with the intensity of the (112)+(111) texture. This could have been caused by the structural banding associated with the components of the texture, or it could be a natural consequence of the improved ballistic limits of the textured plates, because the tendency for spalling usually increases with the impact velocity.[10] The exact cause (or causes) for back spalling is not yet known. In the present plates, because of the relatively low levels of the texture intensities, and because

of their relatively small improvements in ballistic limit, no severe back spalling occurred upon ballistic testing. However, various degrees of moderate spalling were indicated in some of the plates. If the size of the penetration hole on the exit side of the plate is taken as an indicator for the tendency for back spalling, it would be interesting to see whether these data could be correlated with the tensile strengths of notched specimens of the plates.

Table IX is a summary of the averaged diameters of the exit holes in ballistic-tested plates. All holes of complete penetration were measured for all the plates that were ballistic-tested. For each hole, two diameters were measured, and the average value was used.

A comparison of these exit-hole diameters with the tensile strengths of the notched plate specimens (Table V) indicates a consistent qualitative agreement between these two measurements for plates of each category. That is, a higher through-thickness tensile strength corresponds to a smaller exit-hole diameter, and vice versa. These observations seem to provide an additional support to the suggestion made earlier by Richmond[9] that the through-thickness tensile strength of notched specimens can be used as an indicator for the back-spalling resistance of the armor plates.

Figures 14, 15, and 16 are photographs of armor plates tested ballistically. Each of these figures contains two pairs of photographs showing the front and back sides of the plates which were

rolled to 60 and 90 percent reductions, or cross-rolled to 60 and 80 percent reductions in final processing. These photographs thus provide a comparison of the mode of entrance and exit of the projectiles among the plates processed differently. Some of the exit holes are noticeably larger because of back spalling.

Summary and Conclusions

The present investigation consisted essentially of three parts: (1) to produce the (110)-type textures with various degrees of intensity in 0.5-inch-thick armor plates by quenching the isothermally rolled (at 1500°F) and recrystallized (at 1800°F) austenite that had developed a cube texture upon recrystallization; (2) to produce armor plates of the same thickness with the ~(111)-type texture of various intensities by quenching isothermally cross-rolled (at 1500°F) austenite; and (3) to determine the effects of these crystallographic textures on the mechanical and ballistic properties of the plates. To introduce some dislocation substructures in the recrystallized austenite grains before martensite transformation, part of the material in (1) was slightly deformed (by the final pass of rolling) after the recrystallization anneal, then quenched.

Results of the present investigation can be summarized as follows:

1. The (110)-type texture developed in the 0.5-inch-thick armor plates by quenching the isothermally rolled and recrystallized austenite was substantially stronger than that in similar plates produced in an earlier investigation.[1)] The intensity maxima of the

(110) pole figures for plates rolled 60 to 90 percent ranged from 1.65 to 2.80, and were equal to, or better than, the intensities achieved in small-size exploratory specimens processed previously.[1)]

2. The ballistic limits of these (110)-textured plates, although showing small increases with increasing texture intensity, were not significantly different from those of random-textured plates. This suggests that it would be necessary to further increase the (110) texture intensity substantially to establish the effect of the (110) texture on the ballistic performance of the steel armor plates.

3. The ∿(111)-type texture developed in the 0.5-inch-thick armor plates by quenching the isothermally cross-rolled austenite was almost as strong as that produced in small-size exploratory specimens processed in a previous investigation.[2)] The intensity maxima of the (110) pole figures for the finished plates cross-rolled 60 to 80 percent ranged from 2.02 to 2.45 times random.

4. The ballistic limits of these ∿(111)-textured plates were somewhat higher (by about 100 to 200 fps for the plates cross-rolled 80 percent) than those of random-textured plates. Even at these low levels of the texture intensities, the ballistic limit appeared to increase with increasing texture intensity. For further substantial improvements in the ballistic limit, still higher intensities of the ∿(111) texture would be required.

5. The texture of the plates produced by quenching the isothermally rolled and recrystallized austenite to which a light

deformation was applied (by the final pass of rolling) before quenching was a mixture of the (110) and the (112)+(111) textures. The relative amount of these two types of texture varied in the specimens, depending on the total rolling reduction of the plate. For the heavily rolled plates, the (110) texture was stronger than the (112)+(111) texture, whereas for the more lightly rolled plates, the reverse was indicated. This was apparently due to the fact that the amount of reduction in the final pass corresponded to a higher percentage of the total rolling reduction in the lightly rolled than in the heavily rolled plates. These hybrid textures would certainly make the study of the effect of texture on the ballistic properties of the plates even more complex.

6. The ballistic limits of these hybrid-textured plates were all fairly close to those of random-textured plates, consistent with the relatively low levels of texture intensities in these plates. Results from the present investigation also indicated that introducing a light deformation to the cube-textured, recrystallized austenite prior to phase transformation did not produce significant improvements in the ballistic properties.

7. The spalling tendencies of the present plates were mostly weak to moderate, consistent with the fact that the textures of the plates were not strongly developed and that the impact velocities, as indicated by the V_{50} ballistic limits, were not high. By using the average diameter of the exit holes as an indicator for the tendency for back spalling of the plate, it was found that these exit

diameters of the various plates qualitatively correlated with the through-thickness tensile strengths of notched plate specimens. This observation appears to provide additional support to an earlier suggestion by Richmond[9)] that the through-thickness tensile strength of notched specimens should be a measure of the spalling resistance and that the spalling tendency of textured plates is more likely related to the texture than to any increase in impact velocity.

8. The observation that the tendency for back spalling was reduced as texture increased in plates processed to produce a (110)-type texture suggests that if ways can be found to greatly intensify (110-type texture, and if such texture improves ballistic limits, the resulting armor may exhibit a superior ballistic limit without the increased tendency for back spalling that was experienced in earlier results for highly textured steels with (112)+(111) textures.

Future Work

Results and accomplishments from the present and previous investigations suggest that further studies in the immediate future should be conducted in the following directions: (1) Continued investigations for producing steel armor plates with high degrees of intensity and sharpness of the (110), and ∿(111), and perhaps also, the (100) textures, and (2) continued investigations for further strengthening the (112)+(111) texture (whose beneficial effects on the ballistic limits have been well established) by modifying the isothermal rolling process to facilitate the adaption

to commercial mill practice. An improved understanding on the transformation texture of cross-rolled austenite, which showed much lower intensities than that of straightaway-rolled austenite, will be of academic and practical interest.

Acknowledgements

Sincere appreciation is hereby extended to S. Gilbert, R. C. Adams, and R. J. Williams for making the melts, to G. E. Kennedy and C. J. Jennings for conducting the rolling, to R. W. Vanderbeck, R. Alexander, and S. Brejda for the tempering and ballistic testing of the plates, and to R. P. L. Hartley for the chemical analysis of the steels. Competent assistance of R. E. Stecik and P. E. Toohill in making X-ray, hardness, and metallographic measurements is sincerely acknowledged. Frequent consultations with L. F. Porter during the course of the work were most helpful and appreciated.

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10. F. R. Larson: AMMRC, Private Communication.

Table I

Chemical Composition of Armor Steel in Weight Percent
(Check Analysis on Processed Plates)

Ingot No.	C	Mn	P	S	Si	Cu	Ni	Mo	V	Al	N	O, ppm
732*												
Plate A	0.39	0.60	0.004	0.004	1.30	1.03	5.65	0.47	0.094	0.042	0.005	25
Plate D	0.39	0.57	0.004	0.003	1.19	1.03	5.57	0.46	0.090	0.078	0.005	25
733**												
Plate A	0.38	0.58	0.003	0.004	1.25	1.05	5.73	0.49	0.066	0.081	0.004	22
Plate C	0.39	0.57	0.003	0.004	1.27	1.04	5.69	0.49	0.064	0.075	0.004	18

*For Ingot 732, Plate A and Plate D represent top and bottom portions of the ingot and were rolled 60 and 90 percent, respectively.

**For Ingot 733, Plate A and Plate C represent top and bottom portions of the ingot and were cross-Rolled 60 and 80 percent, respectively.

Table II

Estimated Dimensions of Cross-Rolled Plates

Dimensions of the Intermediate Pieces, in. (mm)	Cross-Rolling Reductions in Thickness, %	Estimated Dimensions of the Final Plates, in. (mm)
4.75 x 4.75 x 1.40 (121 x 121 x 36)	60	7.50 x 7.50 x 0.55 (190 x 190 x 14)
4.0 x 4.0 x 1.85 (102 x 102 x 47)	70	7.30 x 7.30 x 0.55 (185 x 185 x 14)
3.25 x 3.25 x 2.75 (83 x 83 x 70)	80	7.25 x 7.25 x 0.55 (184 x 184 x 14)

Table III

Tensile Properties of Steel Armor Plates Processed by Quenching Recrystallized Austenite

Plate Designation	Hot-Rolling Reduction, %	Yield Strength, ksi (MPa)			Tensile Strength ksi (MPa)			Reduction in Area, %			Total Elongation, %		
		L	D	T	L	D	T	L	D	T	L	D	T
Recrystallized Austenite Lightly Deformed													
732A-1	60	225.3 (1553)	217.0 (1496)	225.4 (1554)	304.4 (2099)	302.5 (2086)	305.8 (2108)	46.8	51.3	36.9	14.0	14.0	10.5
732B-1	70	228.0 (1572)	220.3 (1519)	226.5 (1562)	300.8 (2074)	300.7 (2073)	303.2 (2091)	46.4	48.3	36.3	13.5	13.5	10.5
732C-1	80	223.1 (1538)	219.7 (1515)	223.2 (1539)	299.5 (2065)	300.2 (2070)	304.1 (2097)	48.7	48.7	32.9	14.0	14.0	10.0
732D-1	90	226.5 (1562)	224.7 (1549)	227.3 (1567)	301.1 (2076)	295.5 (2038)	303.7 (2094)	46.0	51.6	35.5	14.0	14.0	11.5
Recrystallized Austenite Undeformed													
732A-2	60*	216.2 (1491)	218.2 (1505)	215.8 (1488)	299.9 (2068)	295.9 (2040)	299.0 (2062)	49.3	41.6	40.1	14.3	12.7	12.0
732B-2	70	215.5 (1486)	217.8 (1502)	219.6 (1514)	303.1 (2090)	299.8 (2067)	301.6 (2080)	48.2	49.4	38.4	14.5	13.8	12.0
732C-2	80*	218.4 (1506)	217.8 (1502)	219.8 (1516)	296.2 (2042)	300.4 (2071)	298.8 (2060)	51.2	51.2	40.1	14.5	13.9	12.0
732D-2	90	224.2 (1546)	223.5 (1541)	223.9 (1544)	295.5 (2037)	301.5 (2079)	294.2 (2029)	52.0	51.7	39.8	14.0	13.7	12.0

Results represent the averaged values of duplicate specimens tested for each single plate.

*Two plates were taken for the test.

Table IV

Tensile Properties of Steel Armor Plates Processed by Quenching Cross-Rolled Austenite

Plate Designation	Hot-Rolling Reduction, %	Yield Strength, ksi (MPa)			Tensile Strength, ksi (MPa)			Reduction in Area, %			Total Elongation, %		
		L	D	T	L	D	T	L	D	T	L	D	T
733A	60*	219.0 (1510)	217.3 (1498)	218.3 (1505)	309.5 (2134)	308.6 (2128)	308.0 (2124)	46.4	45.7	39.4	13.8	13.1	12.3
733B	70**	231.8 (1598)	227.5 (1569)	224.8 (1550)	305.1 (2104)	311.4 (2147)	308.6 (2128)	46.0	45.6	39.6	13.3	13.0	11.8
733C	80**	238.6 (1645)	242.5 (1672)	232.6 (1604)	308.7 (2128)	311.7 (2149)	307.7 (2122)	46.0	44.2	41.2	13.0	12.4	12.0

Results represent the averaged values of duplicate specimens tested for each single plate.

*Two plates were taken for the test.

**Three plates were taken for the test.

Table V

Through-Thickness Tensile Properties of Notched Specimens of the Variously Processed Steel Armor Plates

Plate Designation	Hot-Rolling Reduction, %	Tensile Strength, ksi (MPa)	Total Elongation, %
Quenched from Recrystallized Austenite Lightly Deformed			
732A-1	60	431.7 (2977)	0.81
732B-1	70	425.4 (2933)	0.55
732C-1	80	380.8 (2626)	0.47
732D-1	90	386.4 (2664)	0.35
Quenched from Recrystallized Austenite Undeformed			
732A-2*	60	369.2 (2546)	0.45
732B-2	70	431.7 (2977)	0.72
732C-2*	80	386.2 (2663)	0.44
732D-2	90	422.0 (2910)	0.55
Quenched from Cross-Rolled Austenite			
733A*	60	408.2 (2815)	0.39
733B**	70	381.4 (2630)	0.36
733C**	80	361.6 (4293)	0.30

Results represent the averaged values of duplicate specimens tested for each single plate.

*Two plates were taken for the test.

**Three plates were taken for the test.

Table VI

Charpy V-Notch Impact Properties of the Variously Processed Steel Armor Plates

Plate Designation	Hot-Rolling Reduction, %	Impact Energy Longitudinal ft-lb	(J)	Impact Energy Transverse ft-lb	(J)
Quenched from Recrystallized Austenite Lightly Deformed					
732A-1	60	16.8	(22.8)	13.6	(18.4)
732B-1	70	17.8	(24.1)	13.3	(18.0)
732C-1	80	19.7	(26.7)	14.9	(20.2)
732D-1	90	19.3	(26.2)	13.6	(18.4)
Quenched from Recrystallized Austenite Undeformed					
732A-2	60	20.1	(27.3)	15.8	(21.4)
732B-2	70	18.5	(25.1)	13.5	(18.3)
732C-2	80	18.3	(24.8)	14.3	(19.4)
732D-2	90	19.4	(26.3)	15.1	(20.5)
Quenched from Cross-Rolled Austenite					
733A	60	17.8	(24.1)	15.0	(20.3)
733B	70	17.5	(23.7)	15.0	(20.3)
733C	80	15.5	(21.0)	15.5	(21.0)

Results represent the average values of duplicate specimens tested for each plate.

Table VII

Ballistic Performance of Armor Plates Processed by Quenching Recrystallized Austenite

Plate Designation	Hot-Rolling Reduction, %	Texture Type	Texture Intensity	Test Plate Thickness, in.	Test Plate Hardness, R_C	Ballistic Limit, V_{50}, fps
Recrystallized Austenite Lightly Deformed						
732A-1	60		1.50 1.80	0.488	53.0	2016
732B-1	70	(110)	1.93 1.80	0.487	54.0	2042
		and				
732C-1	80	(112)+(111)	1.85 1.20	0.486	53.0	1942
732D-1	90		1.70 1.55	0.501	51.0	2127
Recrystallized Austenite Undeformed						
732A-2	60		1.65	0.487	52.0	1958
732B-2	70	(110)	1.90	0.499	51.5	1950
732C-2	80		2.13	0.489	52.5	1982
732D-2	90		2.80	0.489	53.0	2045

Table VIII

Ballistic Performance of Armor Plates Processed by Quenching Cross-Rolled Austenite

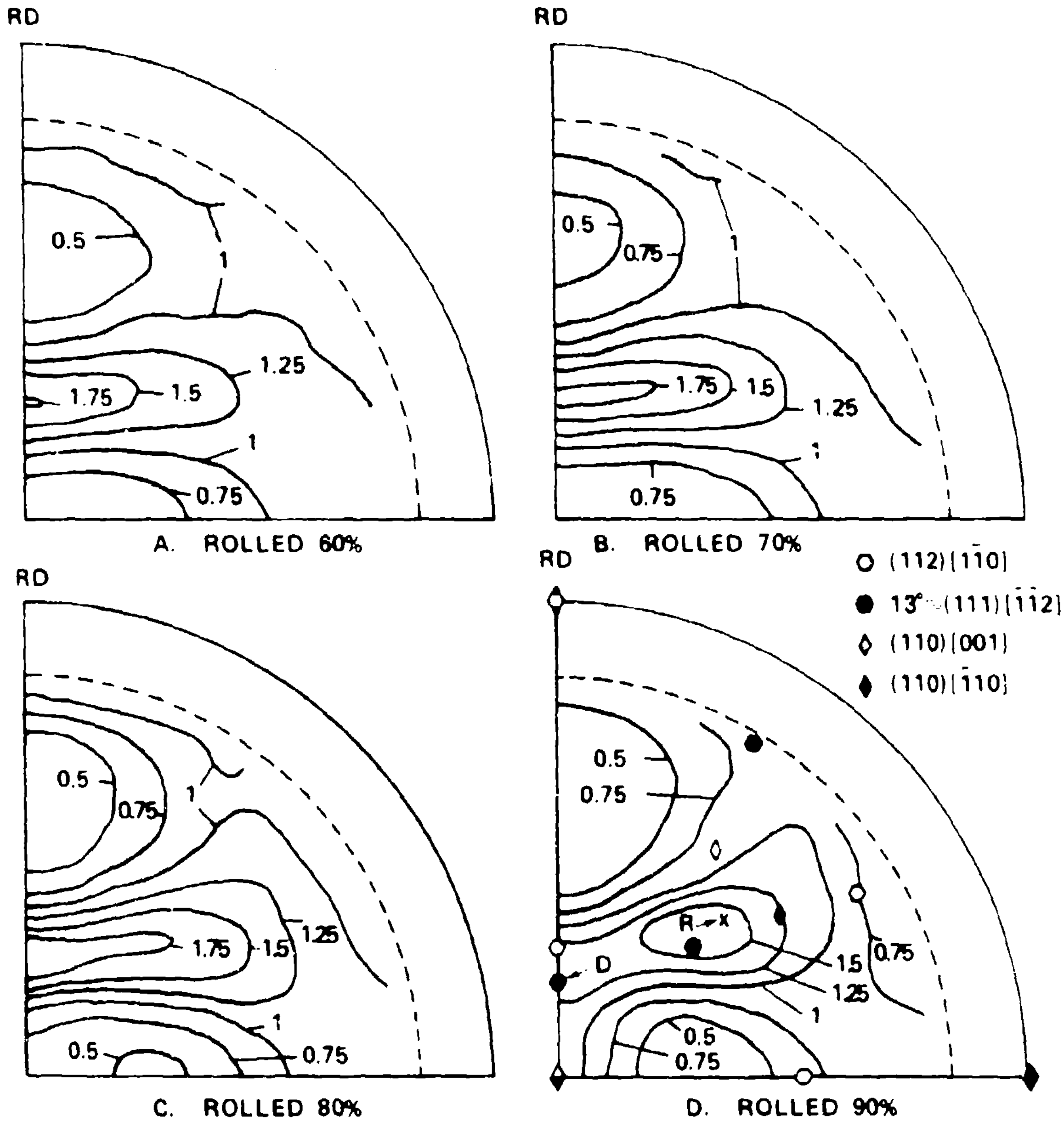
Plate Designation	Hot-Rolling Reduction, %	Texture Type	Texture Intensity	Test Plate Thickness, in.	Test Plate Hardness, R_C	Ballistic Limit, V_{50}, fps
733A	60		2.02	0.491	53.0	2113
733B	70	~(111)	2.29	0.490	53.5	2179
733C	80		2.45	0.489	54.0	2197

The above results represent the averaged values of
2 plates tested for the 60 percent rolled material,
5 plates tested for the 70 percent rolled material,
5 plates tested for the 80 percent rolled material.

Table IX

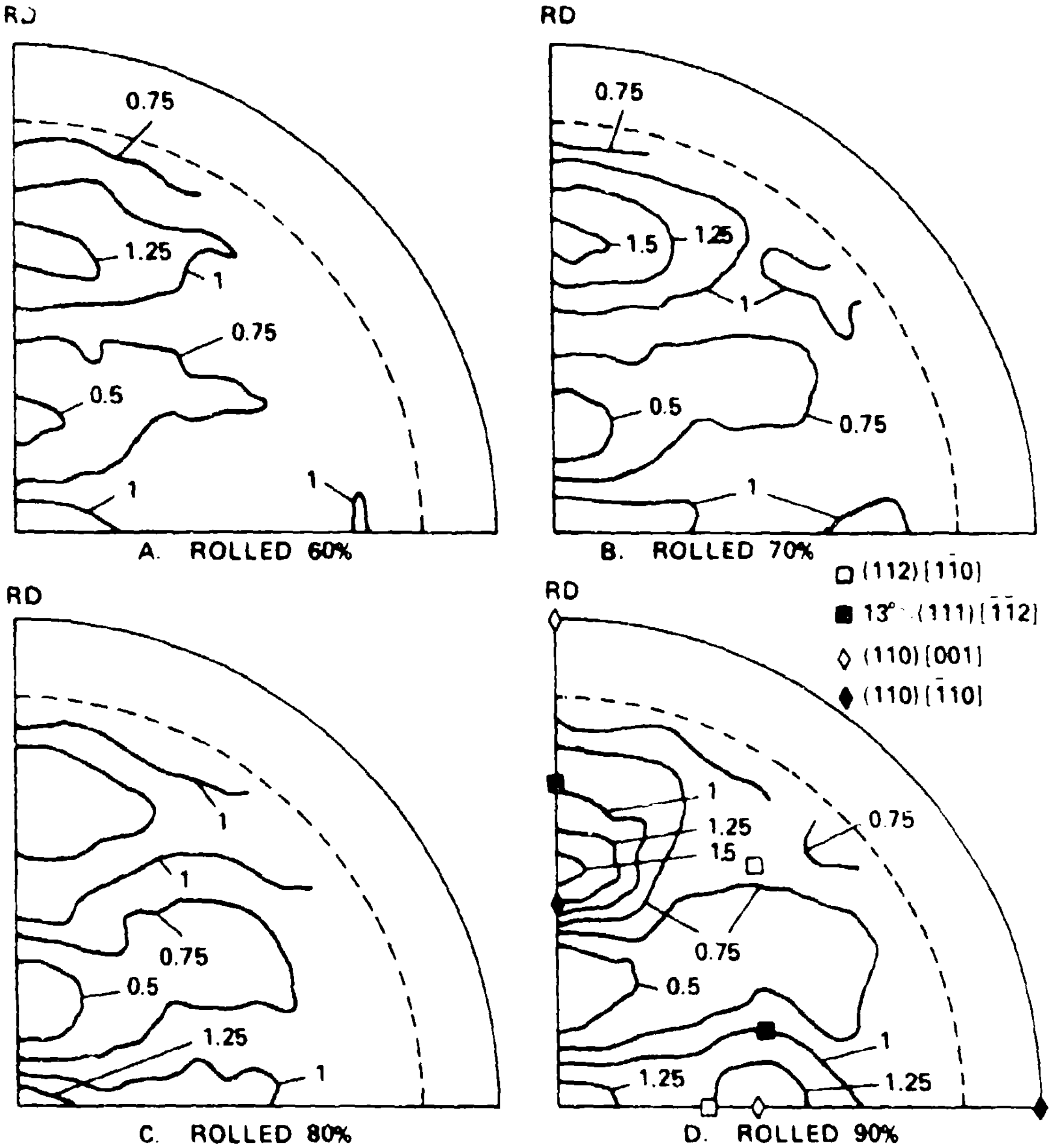
Averaged Diameters of the Exit Holes in Ballistic-Tested Armor Plates

Plate Designation	Hot-Rolling Reduction, %	Exit Hole Diameter, mm	Remarks
Quenched from Recrystallized Austenite Lightly Deformed			
732A-1	60	12.4	5 holes in 1 plate measured
732D-1	90	18.3	2 holes in 1 plate measured
Quenched from Recrystallized Austenite Undeformed			
732A-2	60	11.5	3 holes in 1 plate measured
732D-2	90	10.7	3 holes in 1 plate measured
Quenched from Cross-Rolled Austenite			
733A	60	13.3	5 holes in 2 plates measured
733C	80	14.8	12 holes in 5 plates measured



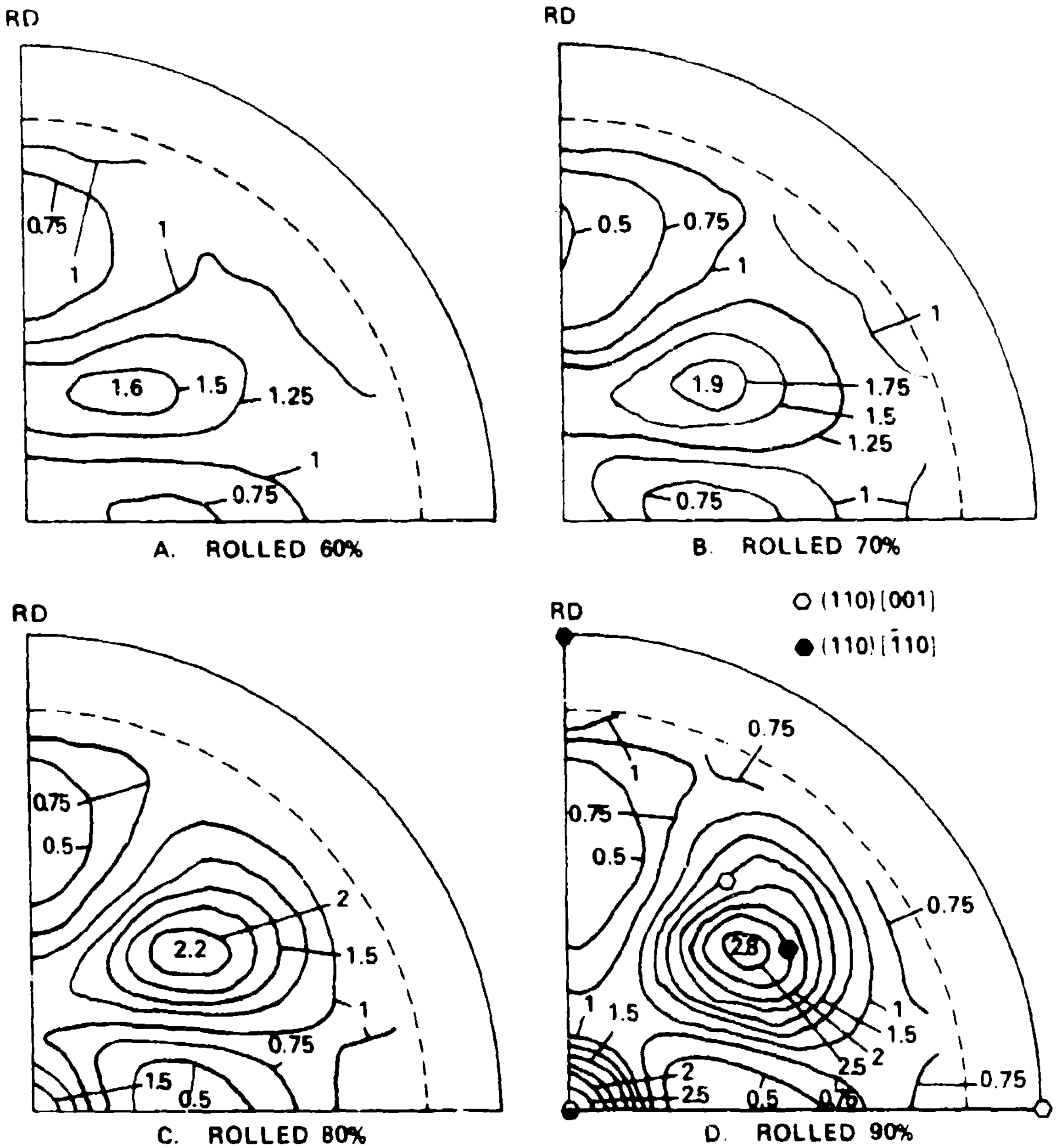
(110) POLE FIGURES OF PLATES ROLLED AT 1500°F TO VARIOUS REDUCTIONS, RECRYSTALLIZED, LIGHTLY DEFORMED, THEN QUENCHED AND TEMPERED. A. ROLLED 60%; B. ROLLED 70%; C. ROLLED 80%; D. ROLLED 90%.

Figure 1



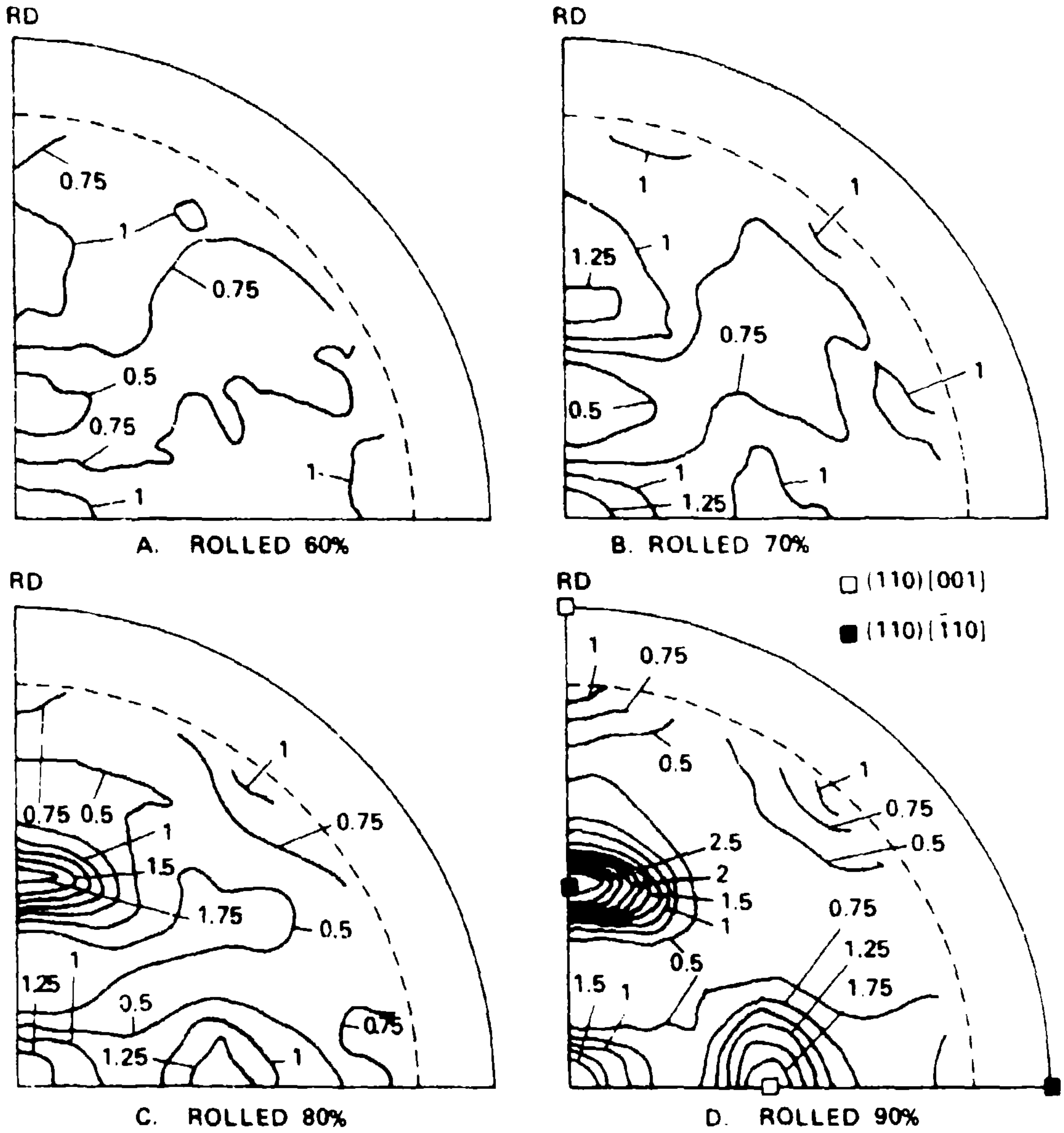
(200) POLE FIGURES OF PLATES ROLLED AT 1500°F TO VARIOUS REDUCTIONS, RECRYSTALLIZED, LIGHTLY DEFORMED, THEN QUENCHED AND TEMPERED. A. ROLLED 60%; B. ROLLED 70%; C. ROLLED 80%; D. ROLLED 90%.

Figure 2



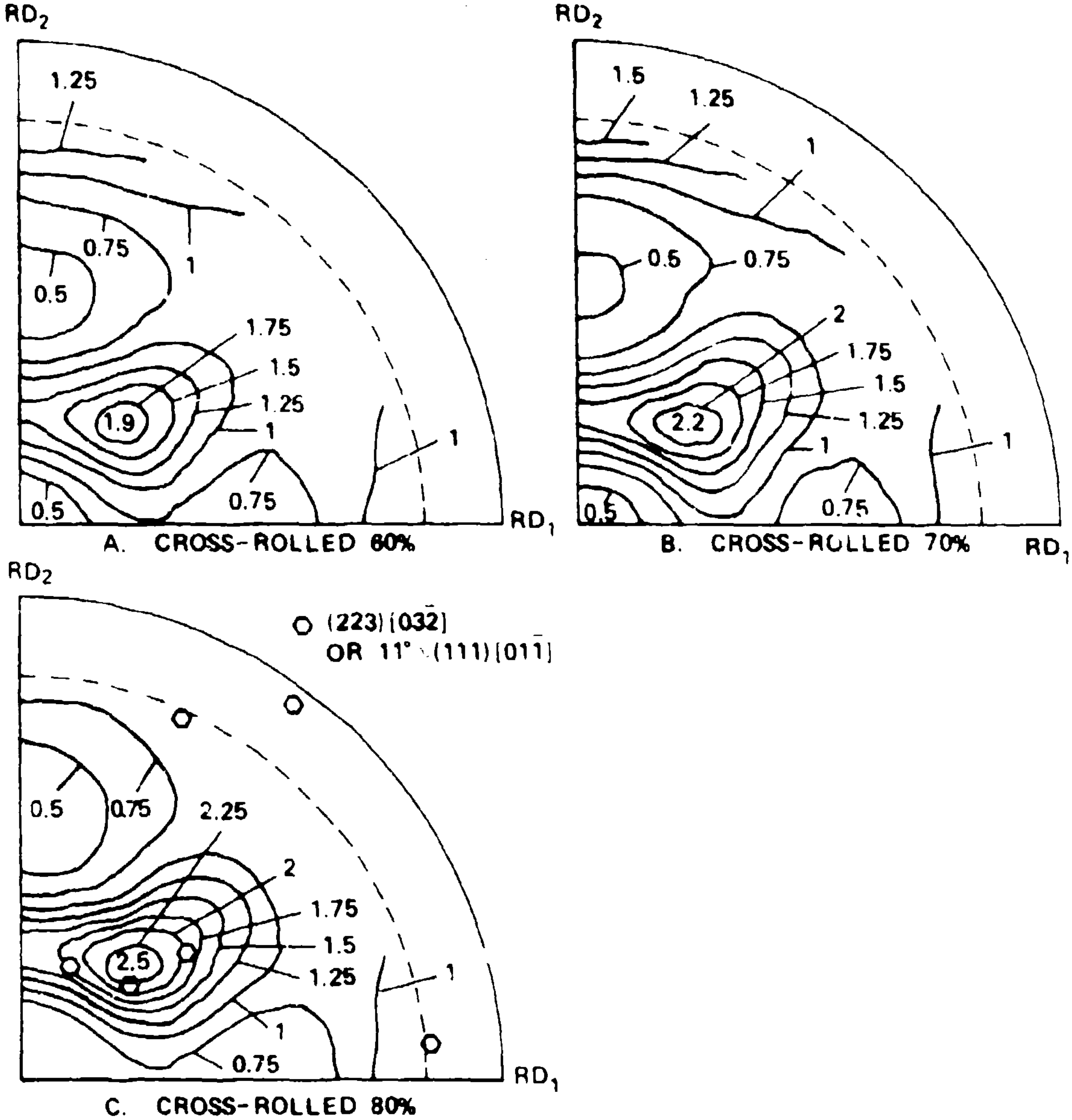
(110) POLE FIGURES OF PLATES ROLLED AT 1500°F TO VARIOUS REDUCTIONS, RECRYSTALLIZED, THEN QUENCHED AND TEMPERED. A. ROLLED 60%; B. ROLLED 70%; C. ROLLED 80%; D. ROLLED 90%.

Figure 3



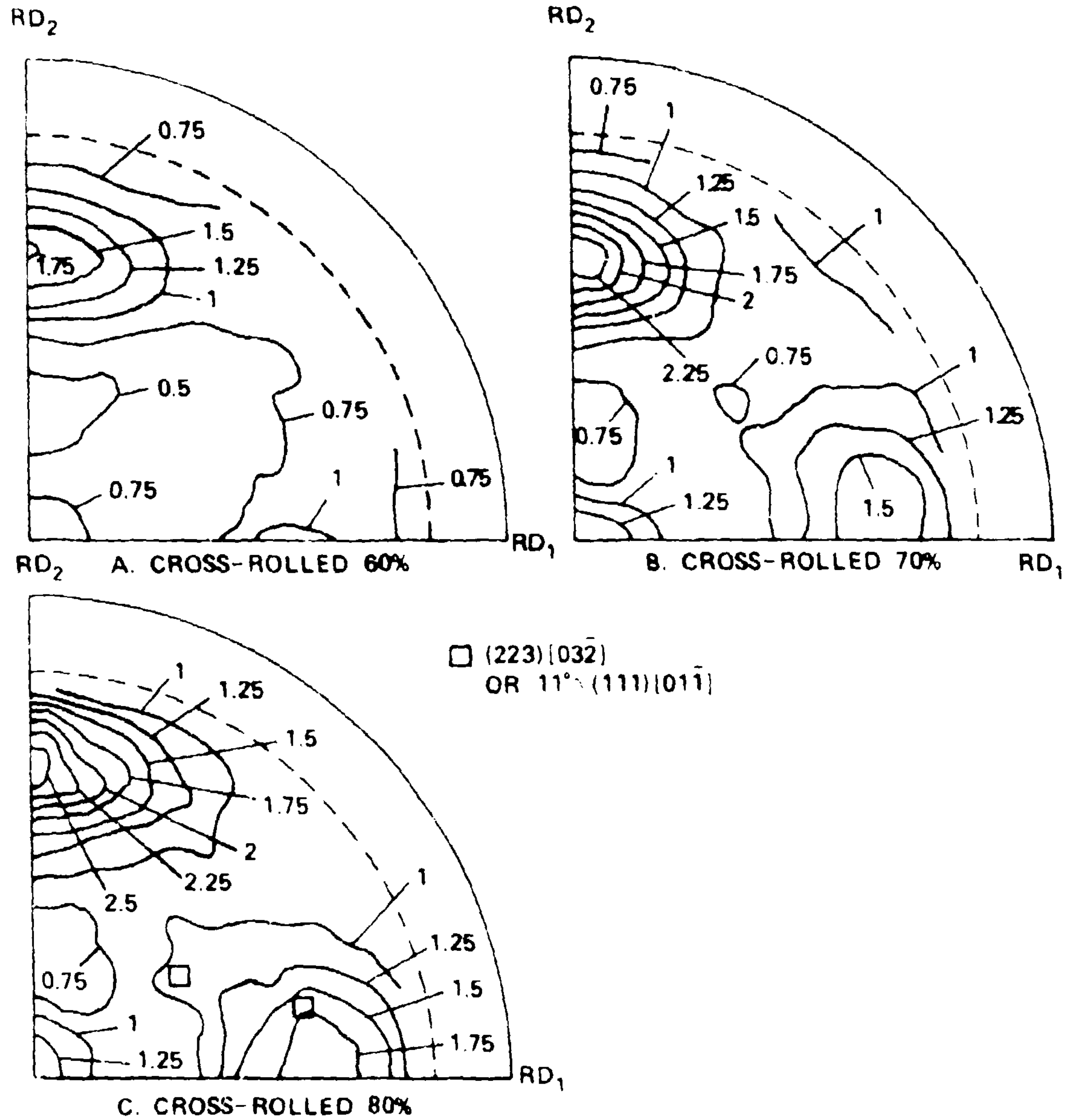
(200) POLE FIGURES OF PLATES ROLLED AT 1500°F TO VARIOUS REDUCTIONS, RECRYSTALLIZED, THEN QUENCHED AND TEMPERED. A. ROLLED 60%; B. ROLLED 70%; C. ROLLED 80%; D. ROLLED 90%.

Figure 4



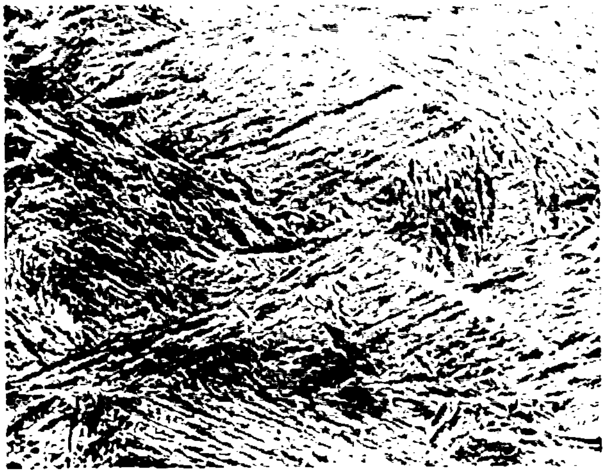
(110) POLE FIGURES OF PLATES CROSS-ROLLED AT 1500°F TO VARIOUS REDUCTIONS, THEN QUENCHED AND TEMPERED A. CROSS-ROLLED 60%; B. CROSS-ROLLED 70%; C. CROSS-ROLLED 80%.

Figure 5

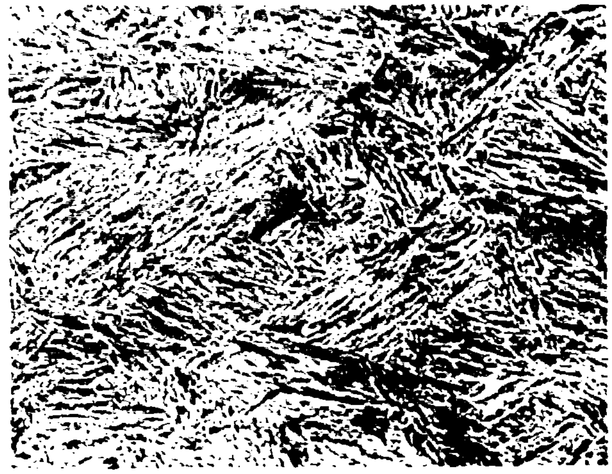


(200) POLE FIGURES OF PLATES CROSS-ROLLED AT 1500°F TO VARIOUS REDUCTIONS, THEN QUENCHED AND TEMPERED. A. CROSS-ROLLED 60%; B. CROSS-ROLLED 70%; C. CROSS-ROLLED 80%.

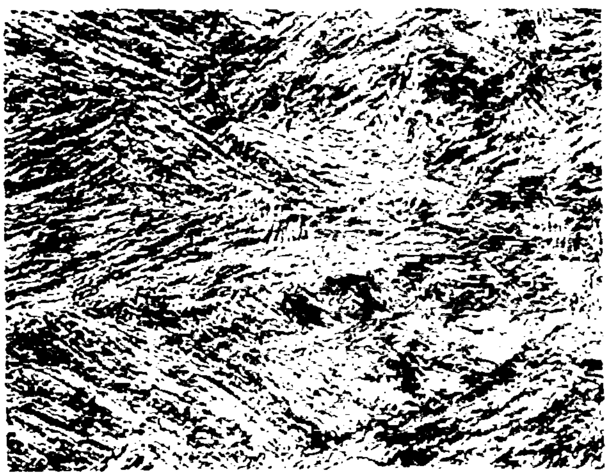
Figure 6



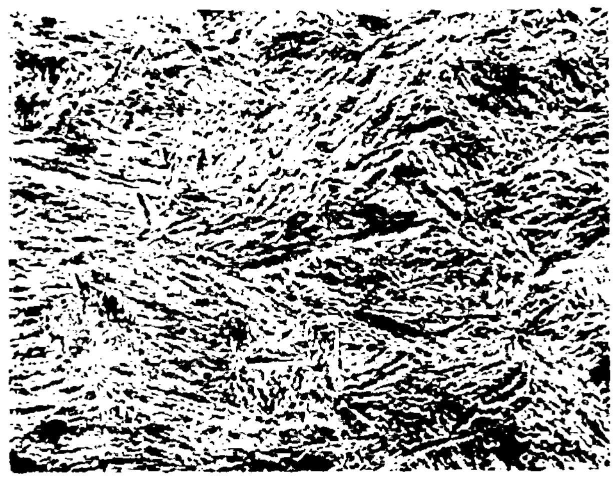
LONGITUDINAL SECTION
ROLLED 60%



TRANSVERSE SECTION
ROLLED 60%



LONGITUDINAL SECTION
ROLLED 90%

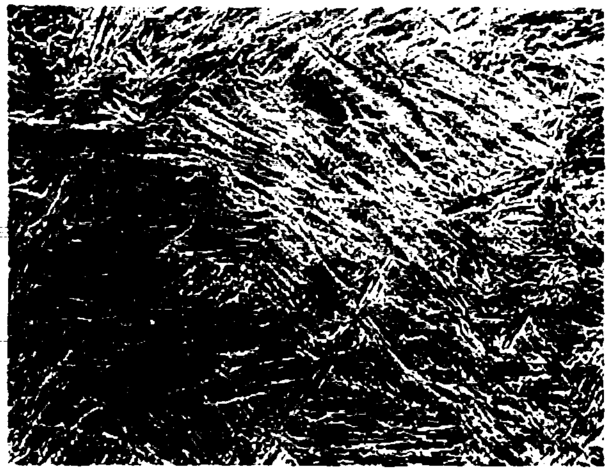


TRANSVERSE SECTION
ROLLED 90%

5 μm

SEM MICROGRAPHS SHOWING STRUCTURES OF PLATES ROLLED AT 1500°F, RECRYSTALLIZED, LIGHTLY DEFORMED, THEN QUENCHED AND TEMPERED. THICKNESS DIRECTION VERTICAL. NITAL ETCH.

Figure 7

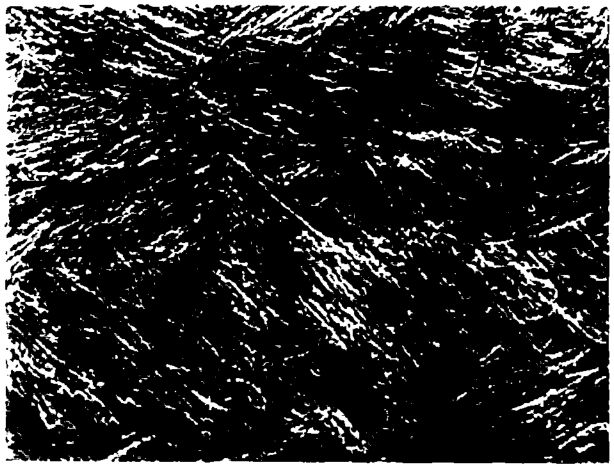


LONGITUDINAL SECTION
ROLLED 60%

TRANSVERSE SECTION
ROLLED 60%

LONGITUDINAL SECTION
ROLLED 90%

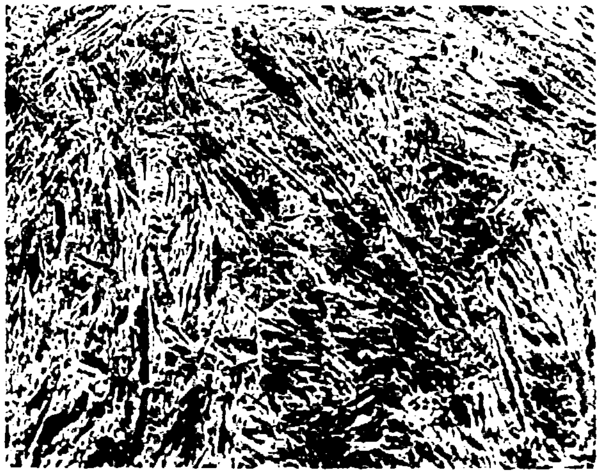
5 μm



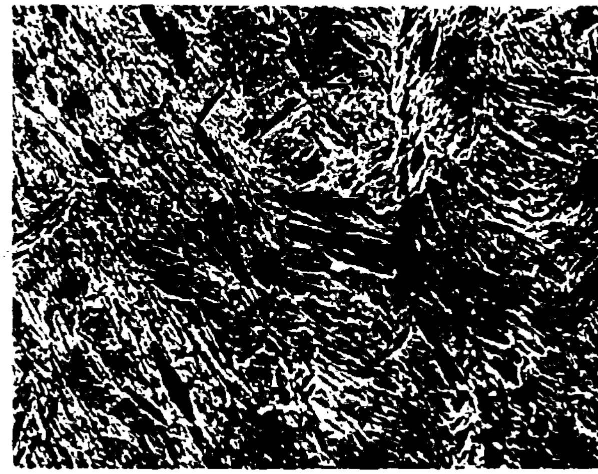
TRANSVERSE SECTION
ROLLED 90%

SEM MICROGRAPHS SHOWING STRUCTURES OF PLATES ROLLED AT 1500°F, RECRYSTALLIZED, THEN QUENCHED AND TEMPERED. THICKNESS DIRECTION VERTICAL. NITAL ETCH.

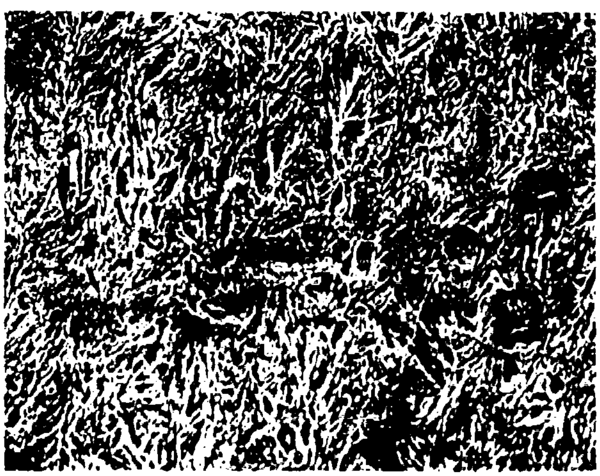
Figure 8



SECTIONED PERPENDICULAR TO RD_1
CROSS-ROLLED 60%

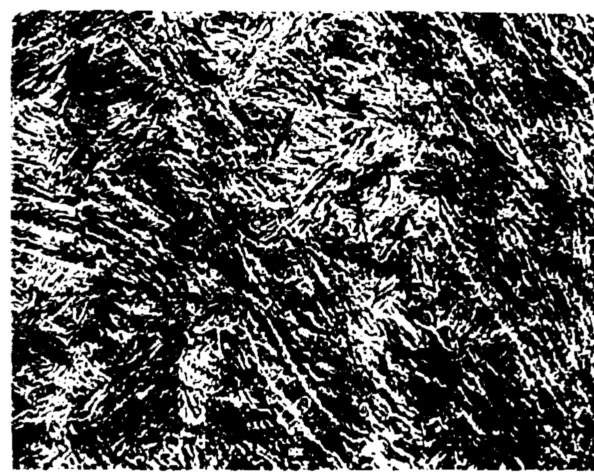


SECTIONED PERPENDICULAR TO RD_2
CROSS-ROLLED 60%



SECTIONED PERPENDICULAR TO RD_1
CROSS-ROLLED 80%

5 μm



SECTIONED PERPENDICULAR TO RD_2
CROSS-ROLLED 80%

SEM MICROGRAPHS SHOWING STRUCTURES OF PLATES CROSS-ROLLED AT 1500°F, THEN QUENCHED AND TEMPERED. THICKNESS DIRECTION HORIZONTAL. NITAL ETCH.

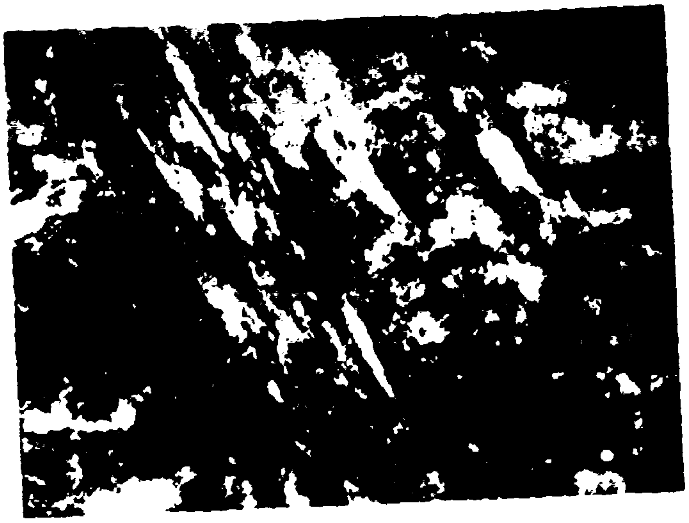
Figure 9

LONGITUDINAL SECTION
ROLLED 60%

TRANSVERSE SECTION
ROLLED 60%

LONGITUDINAL SECTION
ROLLED 90%

1 μm



TRANSVERSE SECTION
ROLLED 90%

TEM MICROGRAPHS SHOWING MARTENSITE STRUCTURES OF PLATES ROLLED AT 1500°F, RECRYSTALLIZED, LIGHTLY DEFORMED, THEN QUENCHED AND TEMPERED.

Figure 10

LONGITUDINAL SECTION
ROLLED 60%

TRANSVERSE SECTION
ROLLED 60%

LONGITUDINAL SECTION
ROLLED 90%

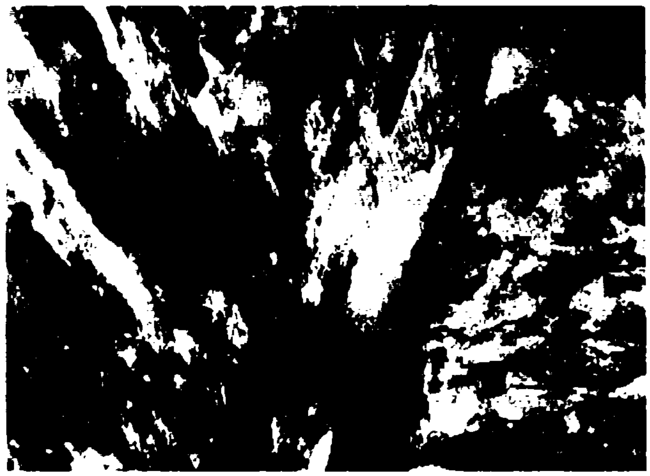
TRANSVERSE SECTION
ROLLED 90%

1 μm

TEM MICROGRAPHS SHOWING MARTENSITE STRUCTURES OF PLATES ROLLED AT 1500°F, RECRYSTALLIZED, THEN QUENCHED AND TEMPERED.

Figure 11

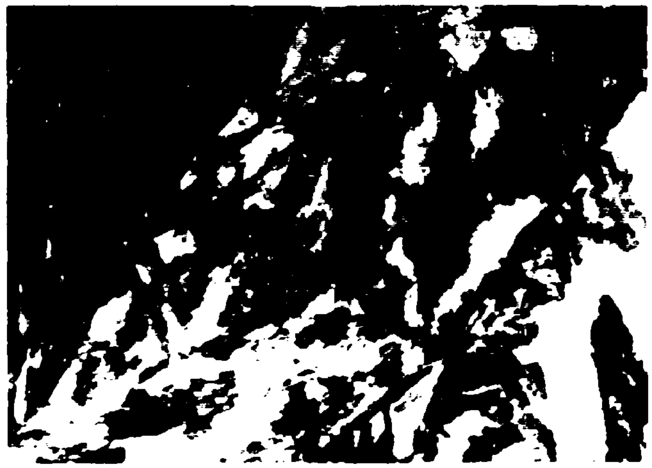
SECTIONED PERPENDICULAR TO RD_1
CROSS-ROLLED 60%



SECTIONED PERPENDICULAR TO RD_2
CROSS-ROLLED 60%

SECTIONED PERPENDICULAR TO RD_1
CROSS-ROLLED 80%

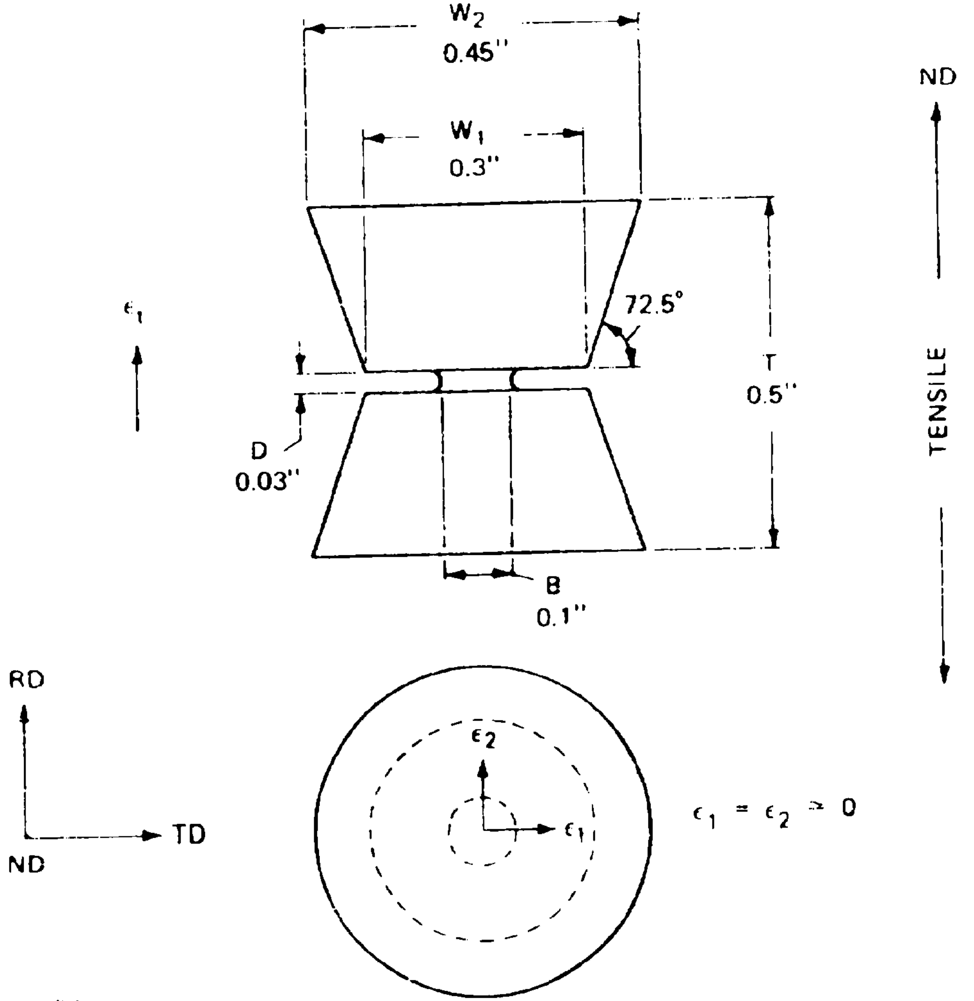
1 μm



SECTIONED PERPENDICULAR TO RD_2
CROSS-ROLLED 80%

TEM MICROGRAPHS SHOWING MARTENSITE STRUCTURES OF PLATES CROSS-ROLLED AT 1500°F, THEN QUENCHED AND TEMPERED.

Figure 12



(B = W/3, D = B/3.3, B = T/5)

SCALE 4:1

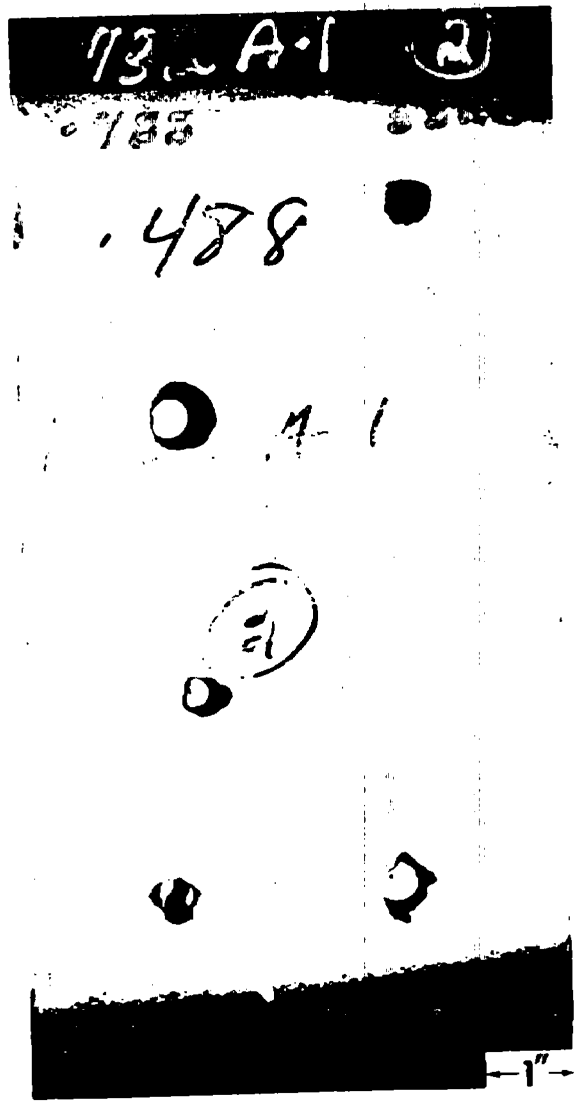
1 inch = 25.4 mm

THROUGH-THICKNESS NOTCHED TENSILE SPECIMEN FOR TESTING SPALLING RESISTANCE OF PLATE (STRAIN RATE CONSTANT)

RL-61-46

Figure 13

FRONT



BACK

BALLISTIC-TESTED PLATE, ROLLED 60% AT 1500°F, RECRYSTALLIZED, LIGHTLY DEFORMED, THEN QUENCHED AND TEMPERED.

Figure 14A

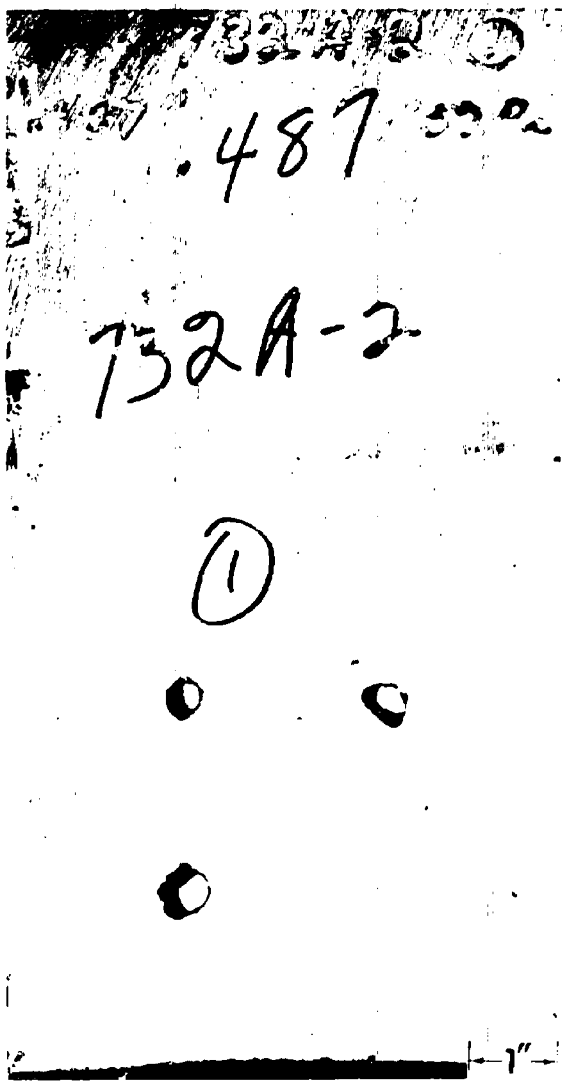
FRONT

BACK

BALLISTIC-TESTED PLATE, ROLLED 90% AT 1500°F, RECRYSTALLIZED, LIGHTLY DEFORMED, THEN QUENCHED AND TEMPERED.

Figure 14B

FRONT

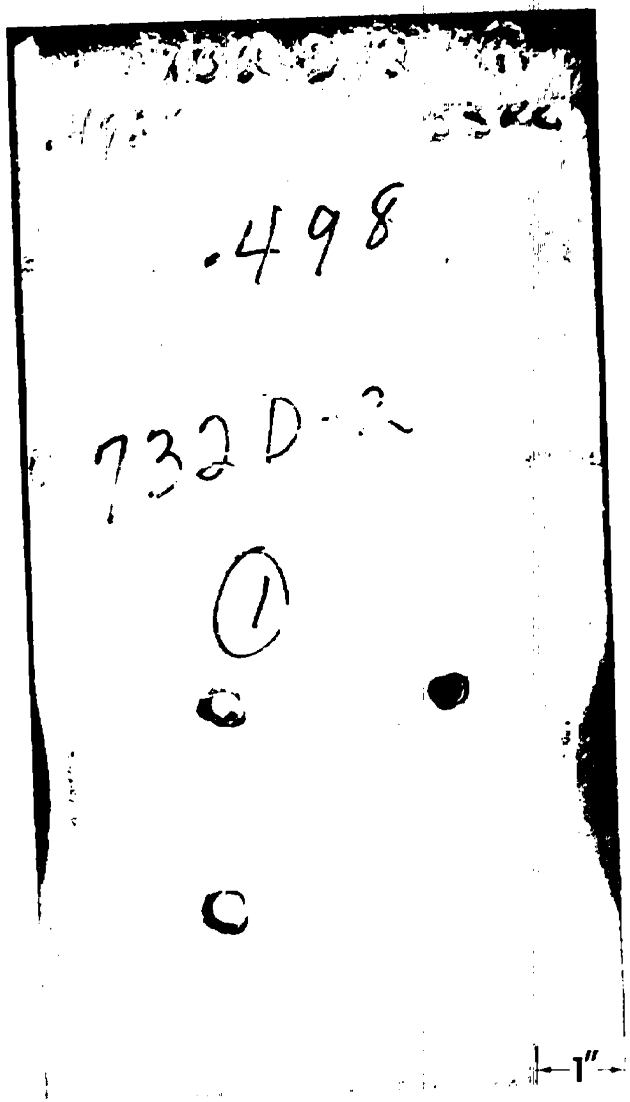


BACK

BALLISTIC-TESTED PLATE, ROLLED 60% AT 1500°F, RECRYSTALLIZED, THEN QUENCHED AND TEMPERED.

Figure 15A

FRONT

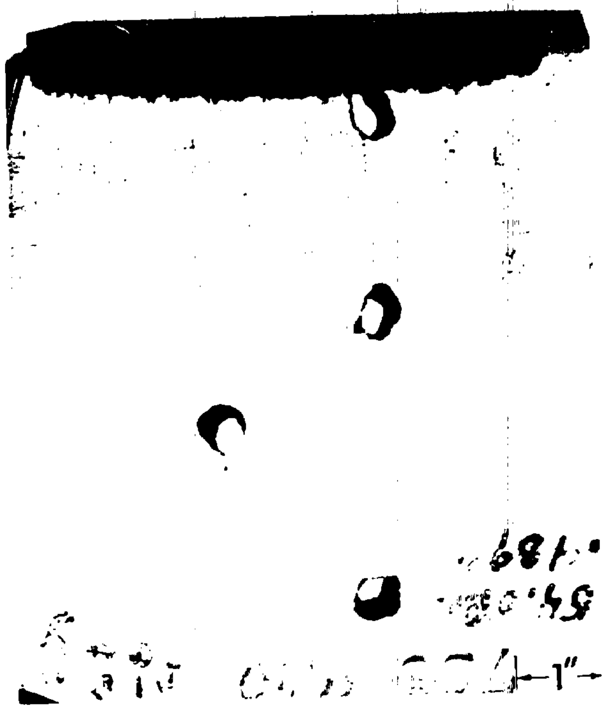


BACK

BALLISTIC-TESTED PLATE, ROLLED 90% AT 1500°F, RECRYSTALLIZED, THEN QUENCHED AND TEMPERED.

Figure 15B

FRONT



BACK

BALLISTIC-TESTED PLATE, CROSS-ROLLED 60% AT 1500°F, THEN QUENCHED AND TEMPERED.

Figure 16A

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Texture	Deformation
Preferred orientation	Ballistics
Alloy steel	Compression tests

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Continuing the study of the effect of crystallographic texture on the mechanical and ballistic properties of steel armor, 1/2-inch-thick plates of a medium-carbon 5Ni-Si-Cu-Mo-V steel were produced with a (110) or an (111) texture of various intensities. Although the intensities of these textures in the present plates (2.80 or 2.45 times random) were as strong as

Block No. 20

ABSTRACT

those in the small-size specimens previously processed under strictly controlled conditions, their effects on the ballistic performance were not sufficiently great to be of practical significance. For both these textures and at the relatively low intensity levels, the V_{50} ballistic limits appeared to increase with increasing texture intensity. Consistent with the relatively low texture intensities and ballistic limits, the spalling tendencies of the plates were mostly weak to moderate. By using the average diameter of the exit holes as an indicator of the tendency for back spalling, a qualitative correlation between the exit diameter and the through-thickness tensile strength of notched plate specimens was found. The application of a light deformation to recrystallized austenite prior to quenching produced a "hybrid" texture in the martensite ai no significant improvements in the ballistic properties. Directions for further investigations in the immediate future are suggested.

Army Materials and Mechanics Research Center,
Watertown, Massachusetts 02172
EFFECT OF CRYSTALLOGRAPHIC TEXTURE ON THE
MECHANICAL AND BALLISTIC PROPERTIES OF STEEL ARMOR
Hsun Hu

Final Technical Report AMMRC TR 78-39, July 1978,
79 pp - illus, DAAG Project 46-77-C-0037
AMCMS Code 612105.11.H8400, Unclassified Report

As a continued study of the effect of crystallographic texture on the mechanical and ballistic properties of steel armor, 1/2-inch-thick plates of a medium-carbon 5Ni-Si-Cu-Mo-V steel were produced with a {110} or an {111} texture of various intensities. Although the intensities of these textures in the present plates (2.80 or 2.45 times random) were as strong as those in the small-size specimens previously processed under strictly controlled conditions, their effects on the ballistic performance were not sufficiently great to be of practical significance. For both these two textures and at the relatively low intensity levels, the V_{50} ballistic limits appeared to increase with increasing texture intensity. Consistent with the relatively low texture intensities and ballistic limits, the spalling tendencies of the plates were mostly weak to moderate. By using the average diameter of the exit holes as an indicator for the tendency of back spalling, it was found that a qualitative correlation between the exit diameter and the through-thickness notched tensile strength of the plates was indicated. The application of a light deformation to recrystallized austenite prior to quenching produced a "hybrid" texture in the martensite and no significant improvements in the ballistic properties. Directions for further investigations in the immediate future are suggested.

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1. Ballistic properties
2. Steel armor
3. Thermomechanical treatment
4. Preferred orientation
5. Retained austenite
6. Texture

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